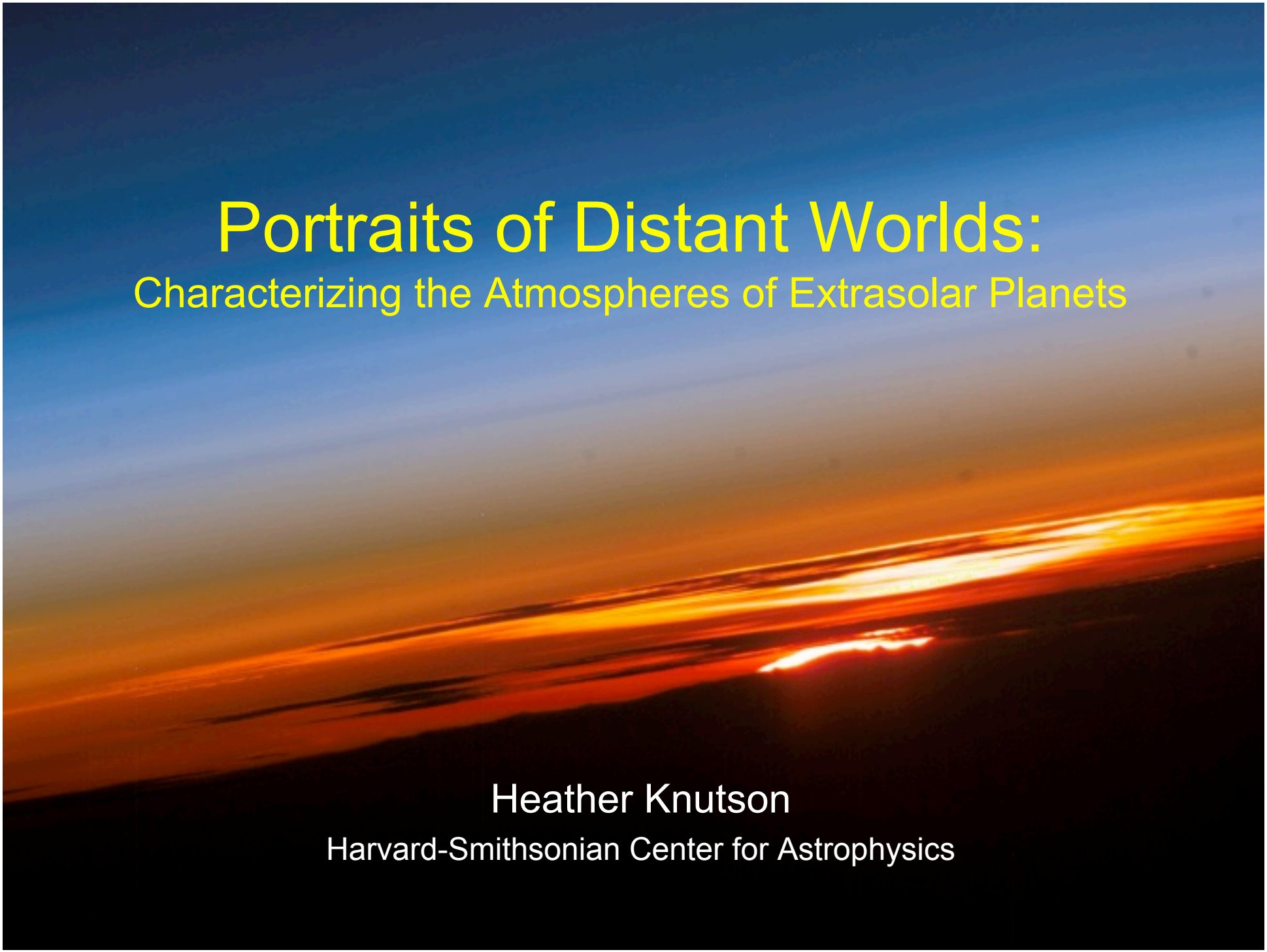


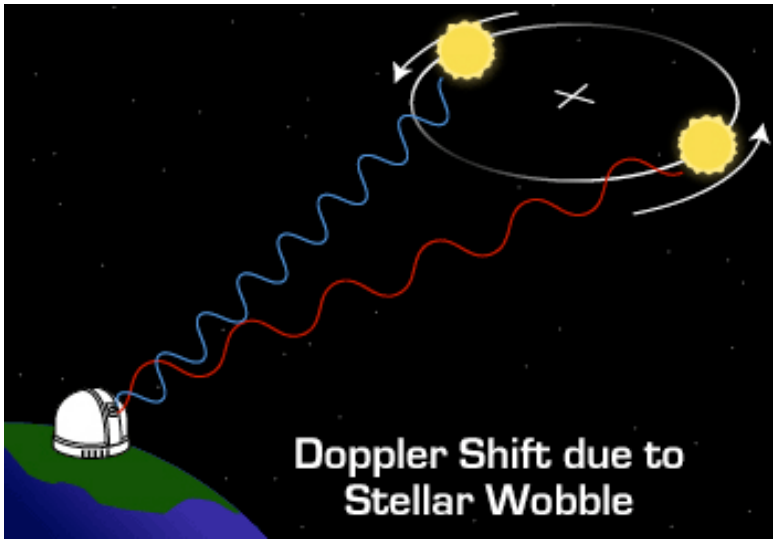
Portraits of Distant Worlds:

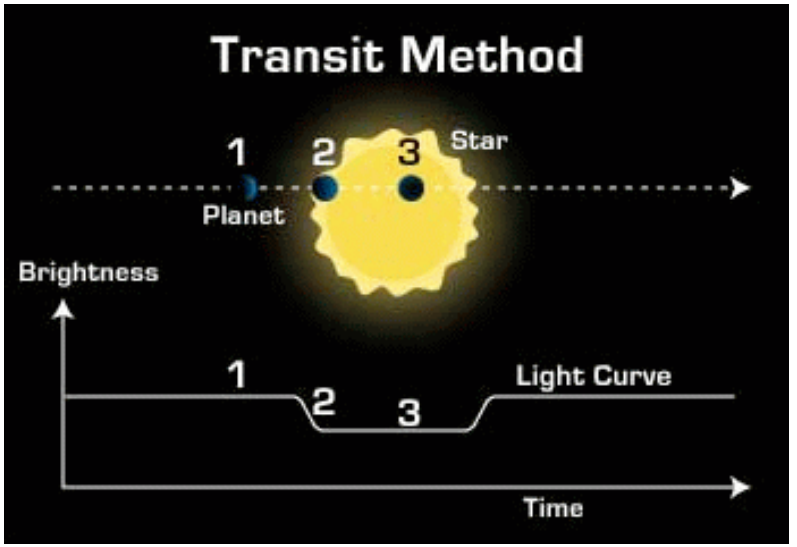
Characterizing the Atmospheres of Extrasolar Planets

Heather Knutson

Harvard-Smithsonian Center for Astrophysics

Two Methods for Studying Exoplanets





Doppler Method

Determine Planet Mass

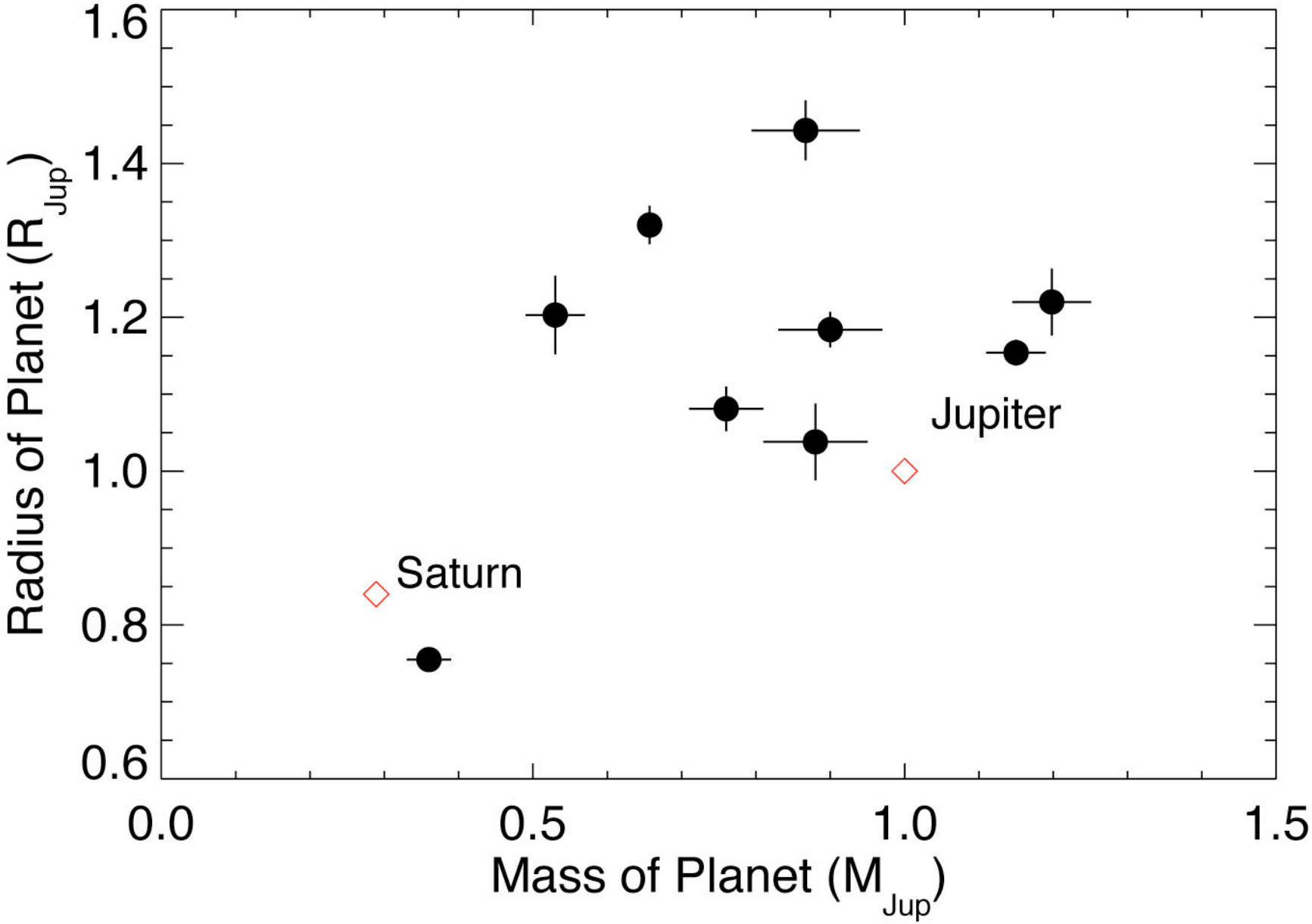
Transit Method

Determine Planet Diameter

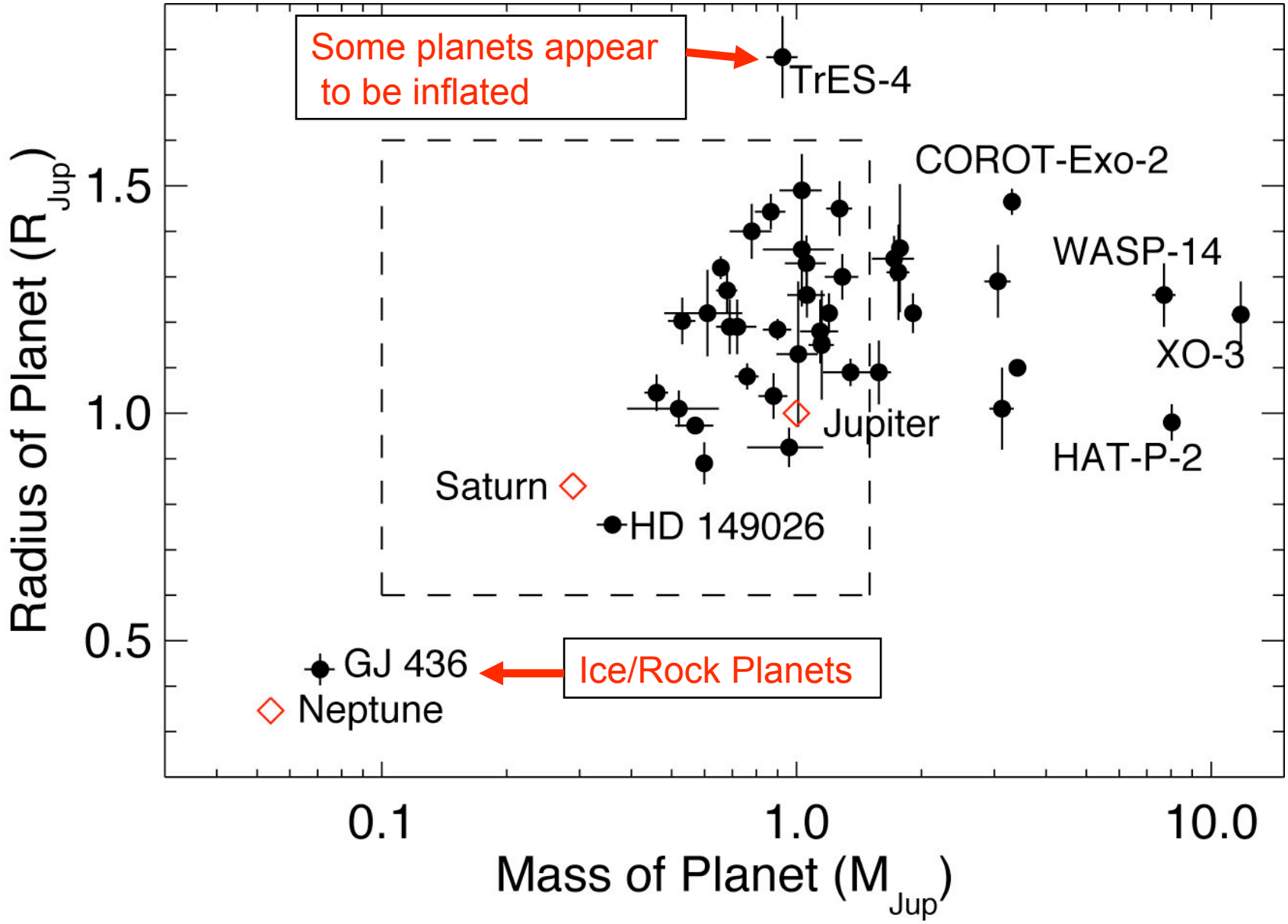
Calculate Planet Density and Infer Composition:

Gas giant (Jupiter), Ice giant (Neptune), or Rocky planet (Earth)

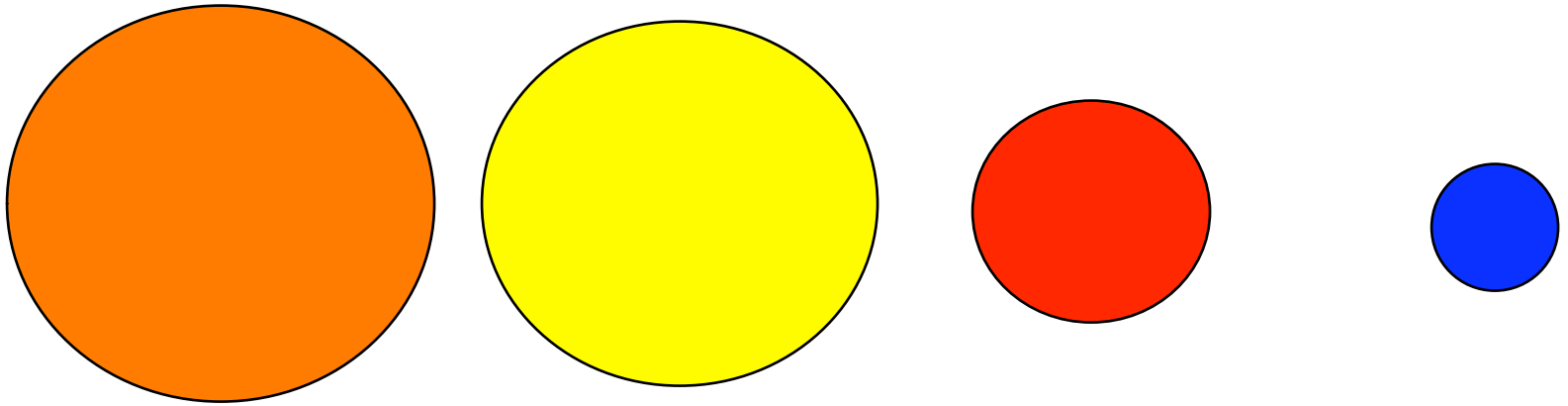
Transiting Planets: May 1, 2007



Transiting Planets Today: 43 Systems And Counting



Four Exoplanets: A Comparison



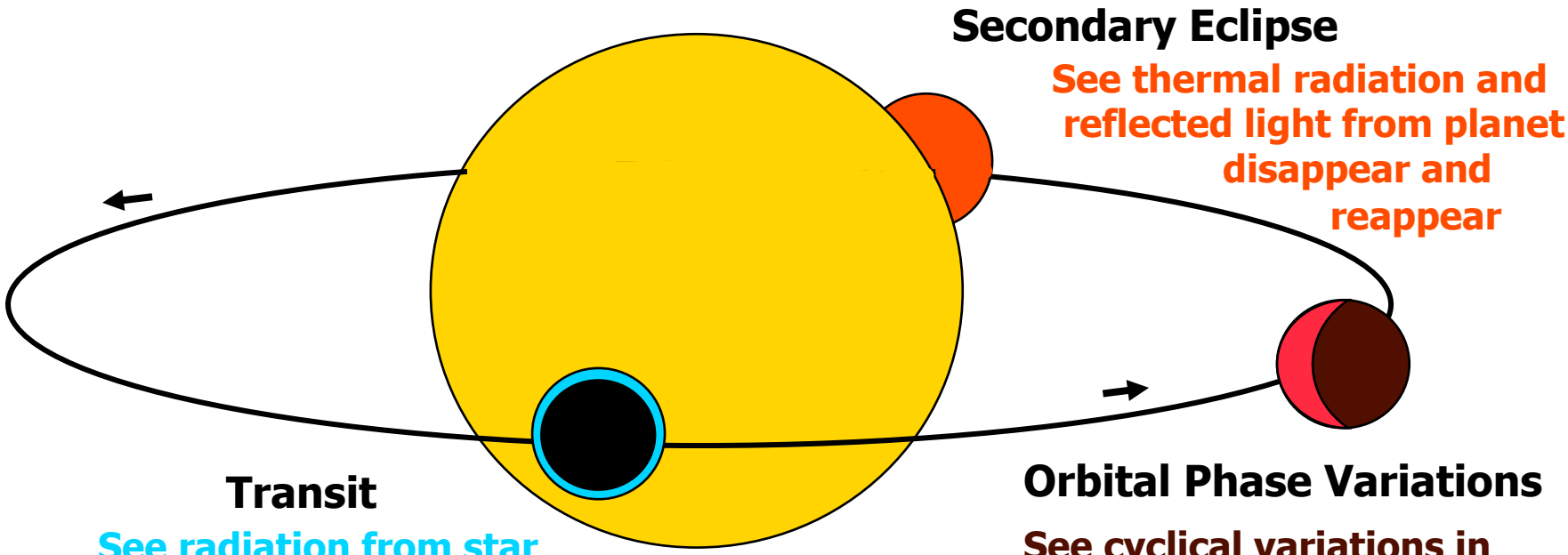
HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1360 K

HD 189733b
Mass: 1.15 M_{Jup}
Radius: 1.15 R_{Jup}
T_{equil}=1130 K

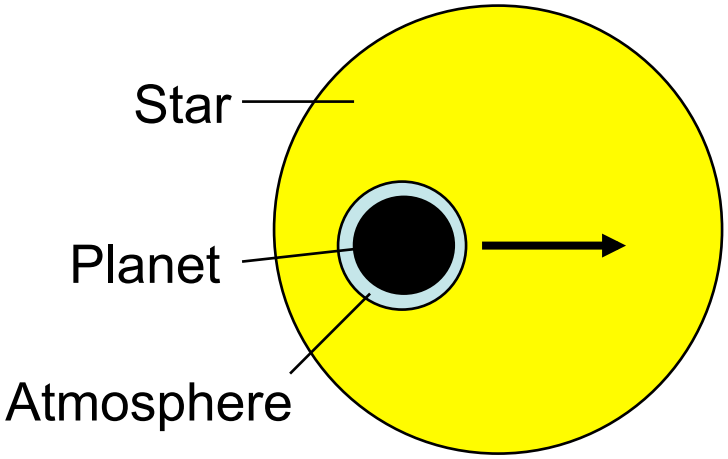
HD 149026b
Mass: 0.36 M_{Jup}
Radius: 0.76 R_{Jup}
T_{equil}=1650 K

GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=670 K

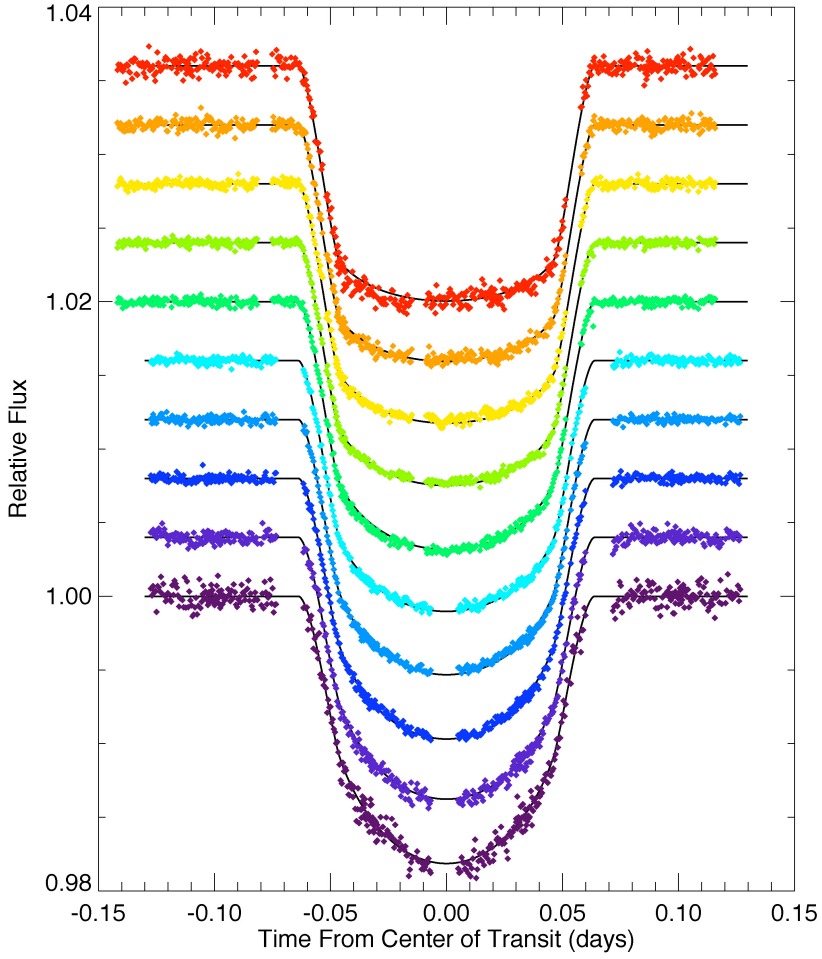
Transiting Planets as a Tool for Studying Exoplanet Atmospheres



Characterizing Atmospheres With Transmission Spectroscopy



- Probes composition of atmosphere at day-night terminator
- Can search for clouds, hazes, condensates



HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)

Water and Haze on HD 189733b

Featureless visible light spectrum indicates hazes…

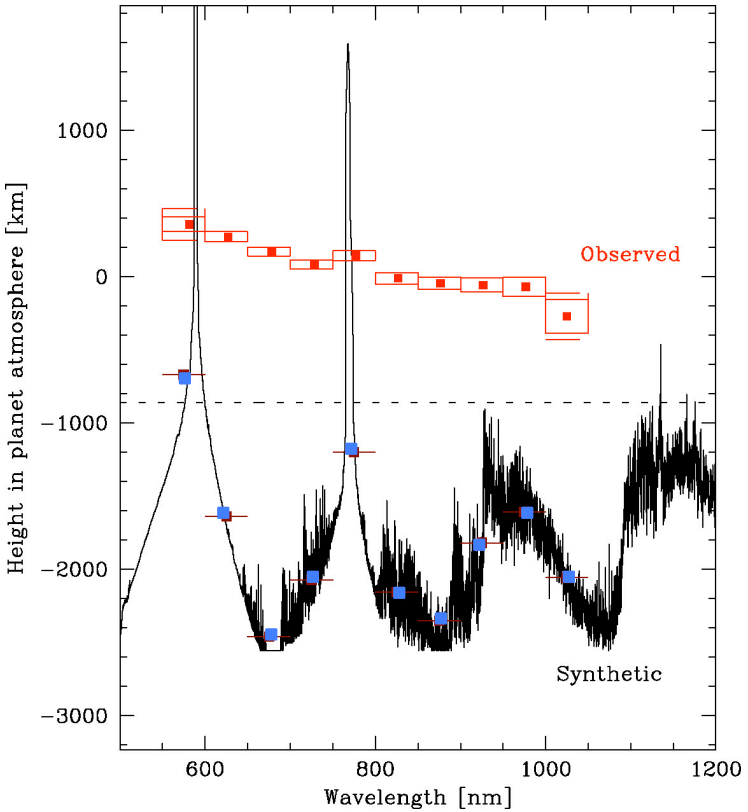


Figure from Pont, Knutson et al. (2007) showing atmospheric transmission function derived from HST ACS measurements between 600-1000 nm

… which disappear in infrared, revealing water absorption features.

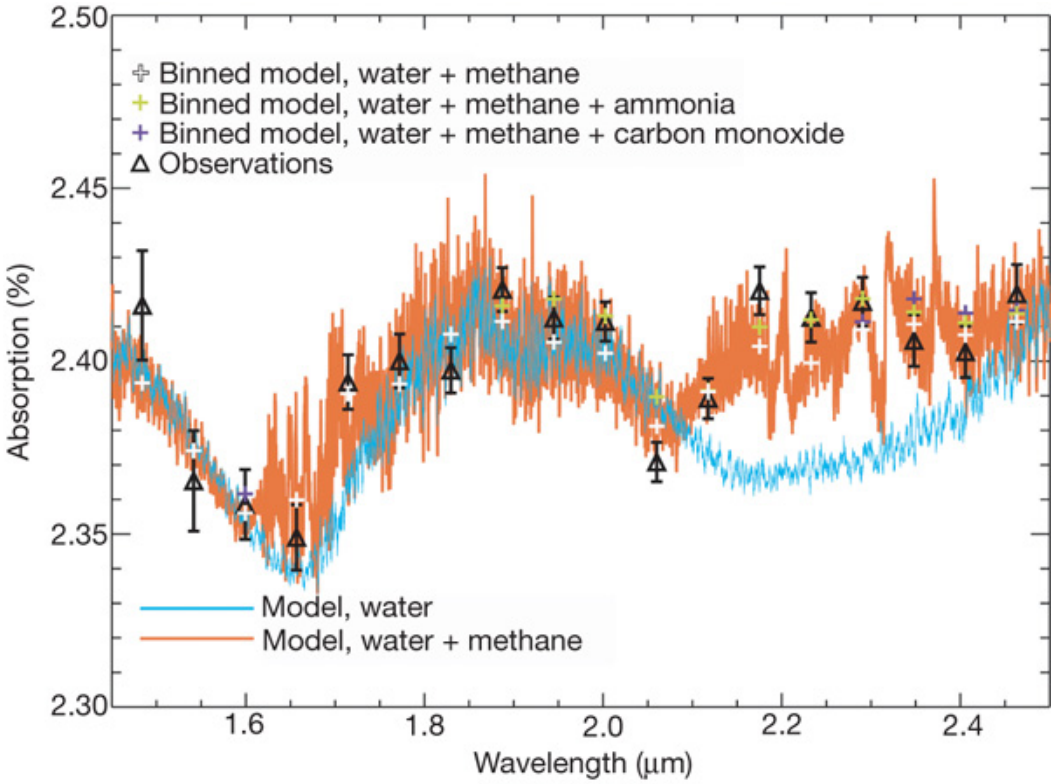
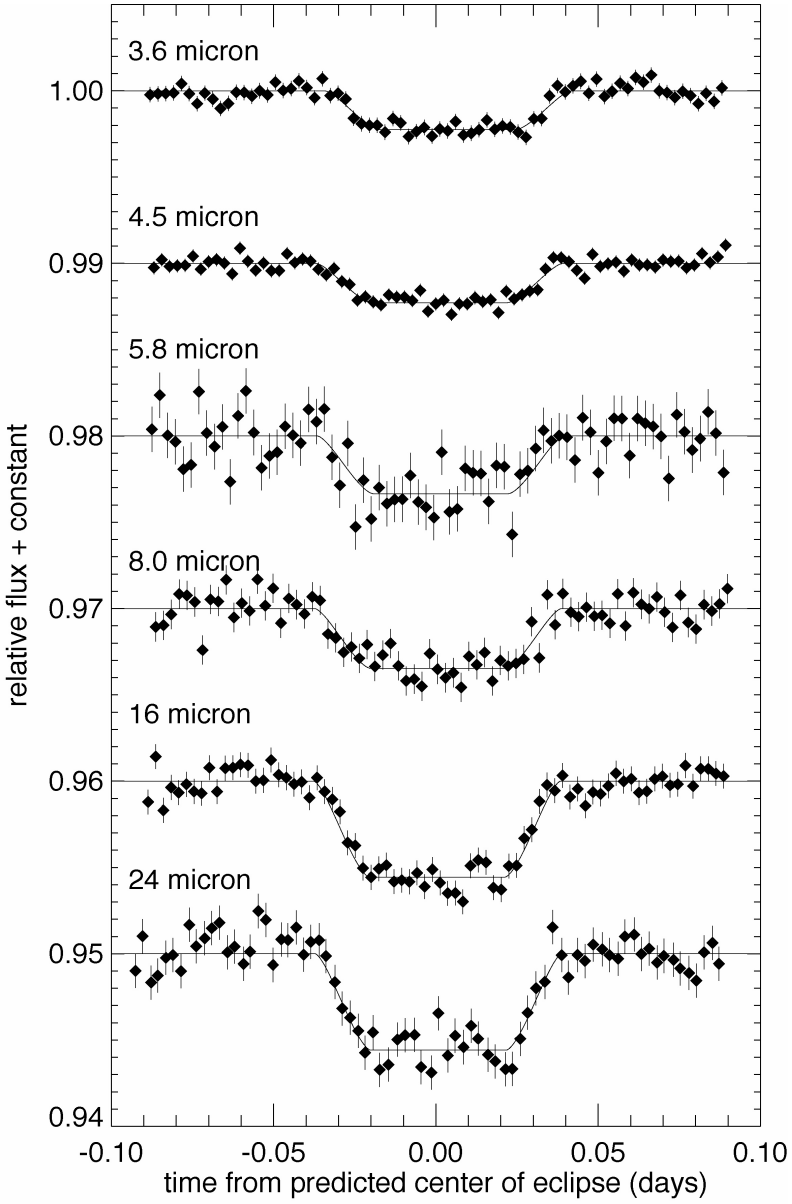
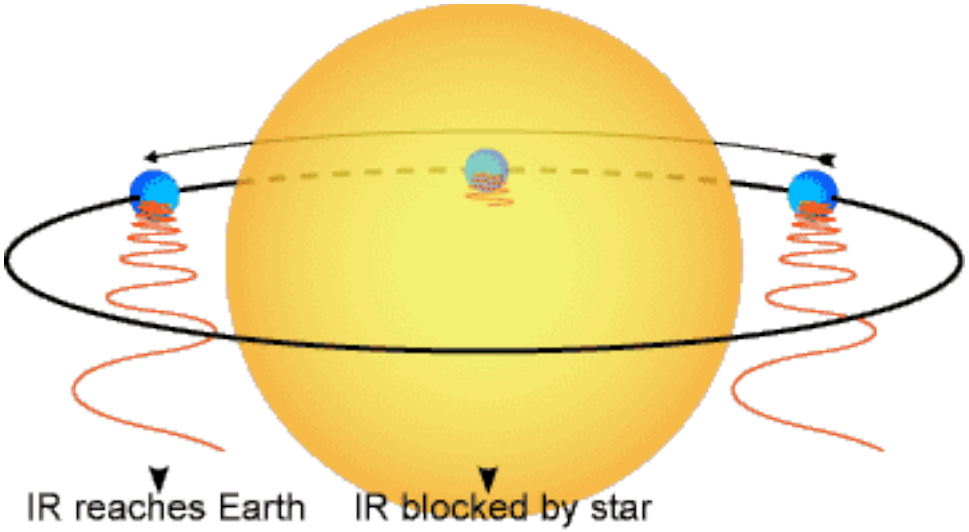


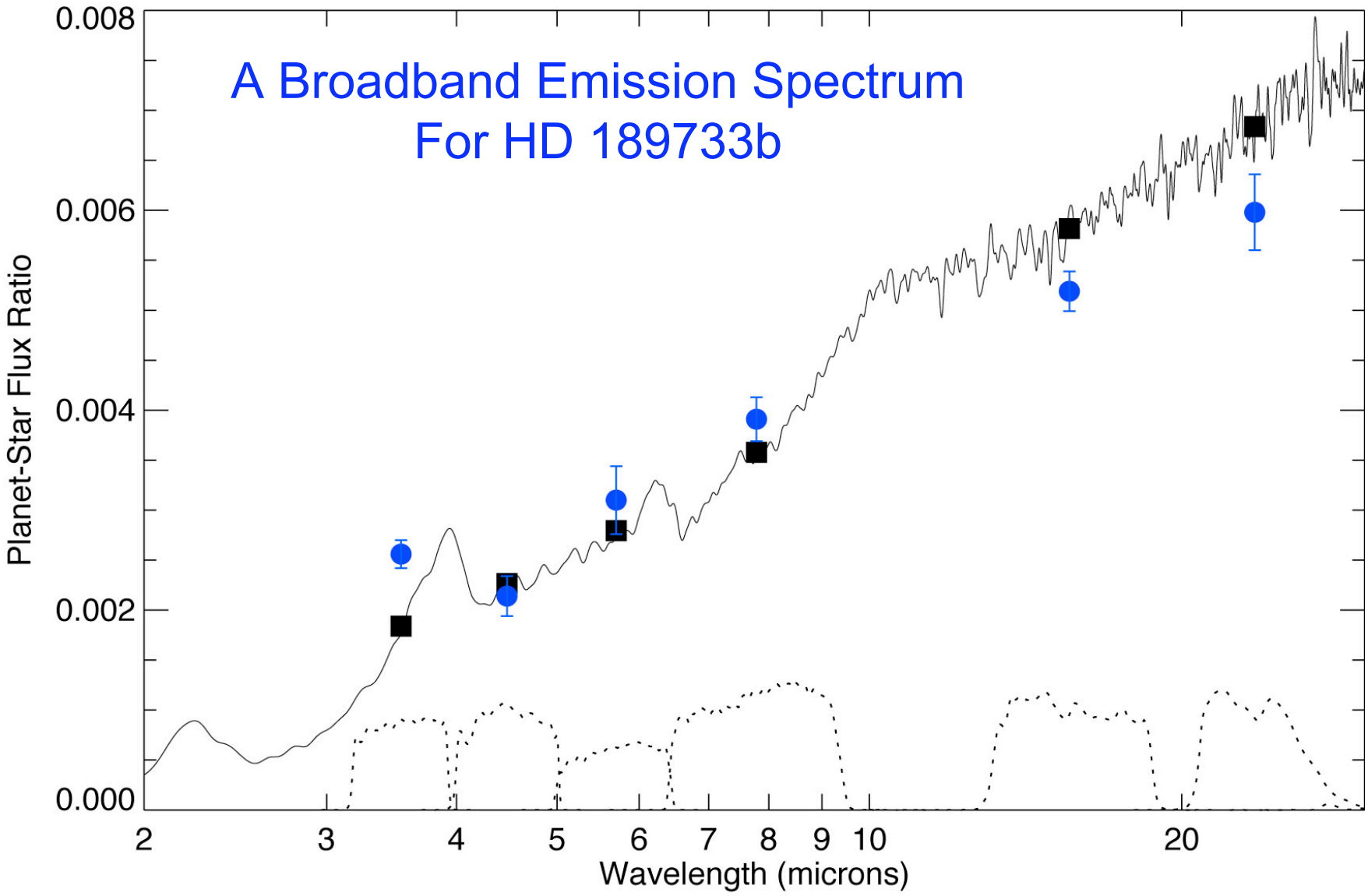
Figure from Swain et al (2008) showing infrared atmospheric transmission function derived from HST NICMOS spectra compared to models for the planet's transmission spectrum with (orange) and without (blue) additional methane absorption (Tinetti et al. 2008).

Spitzer observations of HD 189733b
(Charbonneau, Knutson et al. 2008)



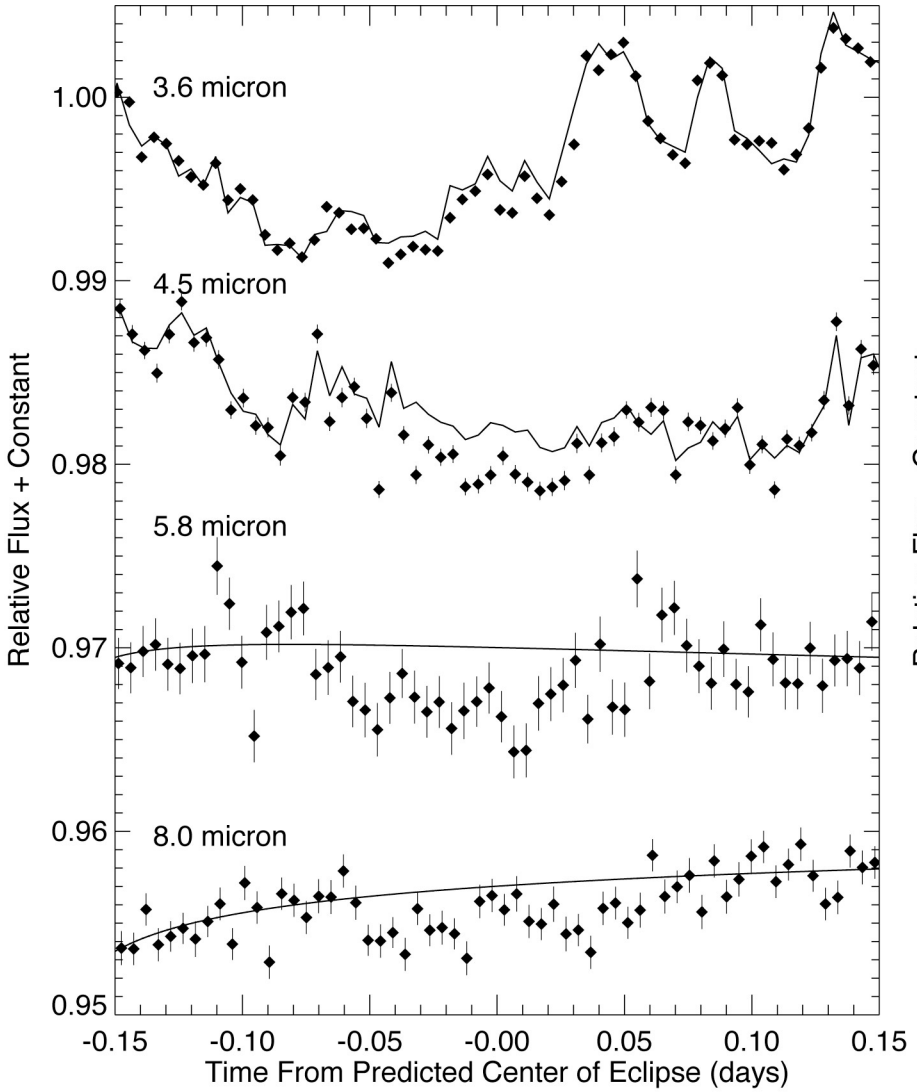
Direct Detection of Thermal Emission From Exoplanets

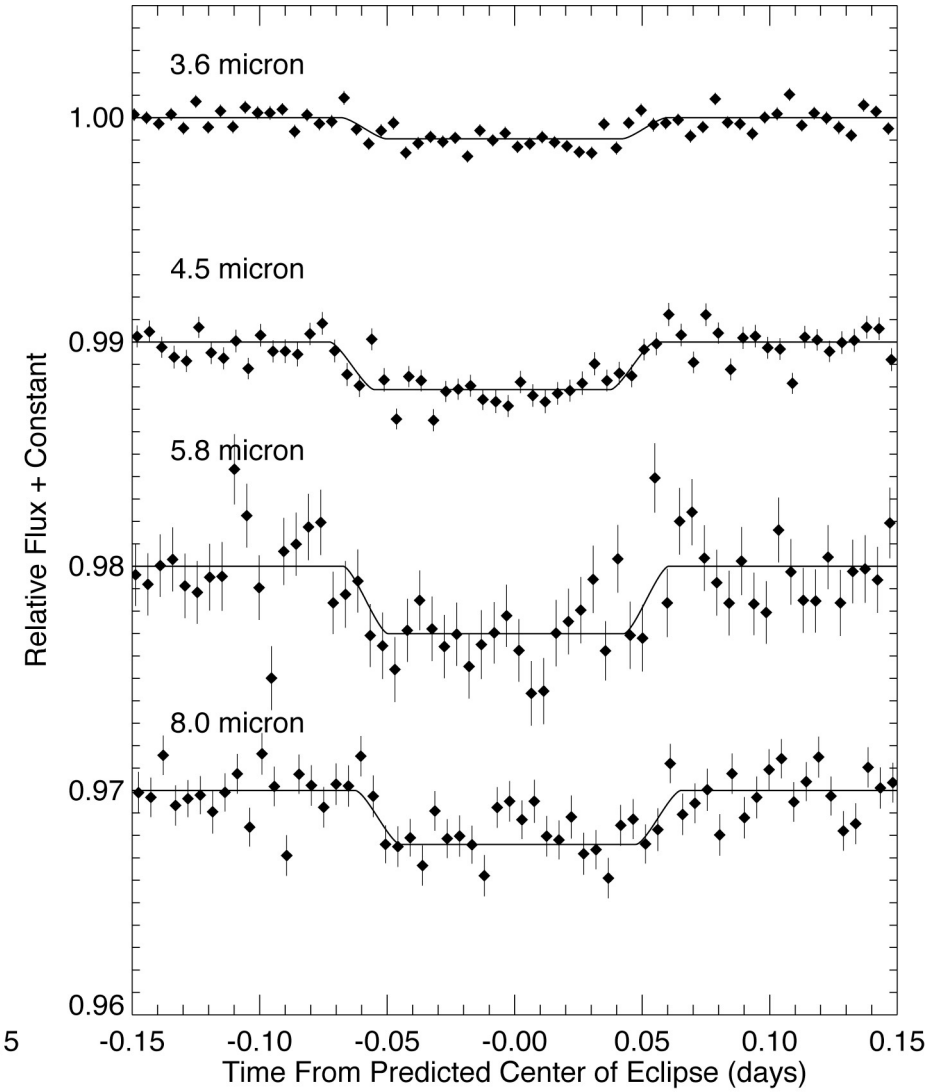




Charbonneau, Knutson et al. (2008), Barman (2008)

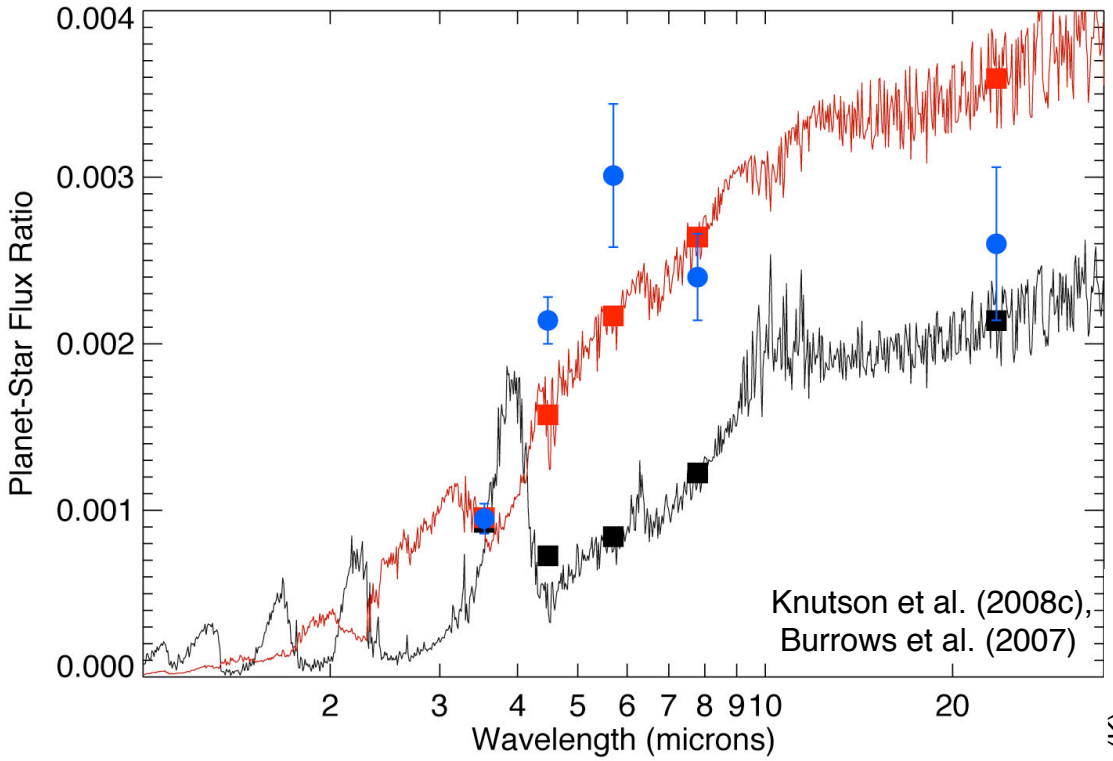
Expanding the Sample: HD 209458b



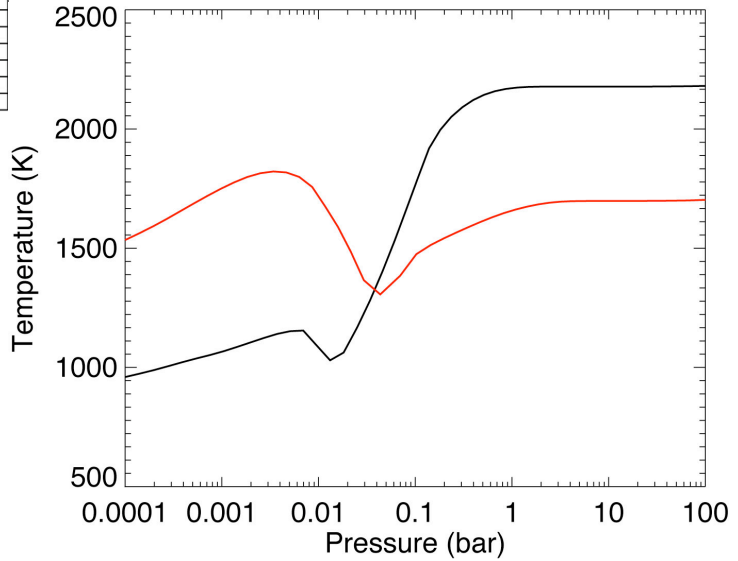


Knutson et al. (2008a)

HD 209458b's Surprising Emission Spectrum

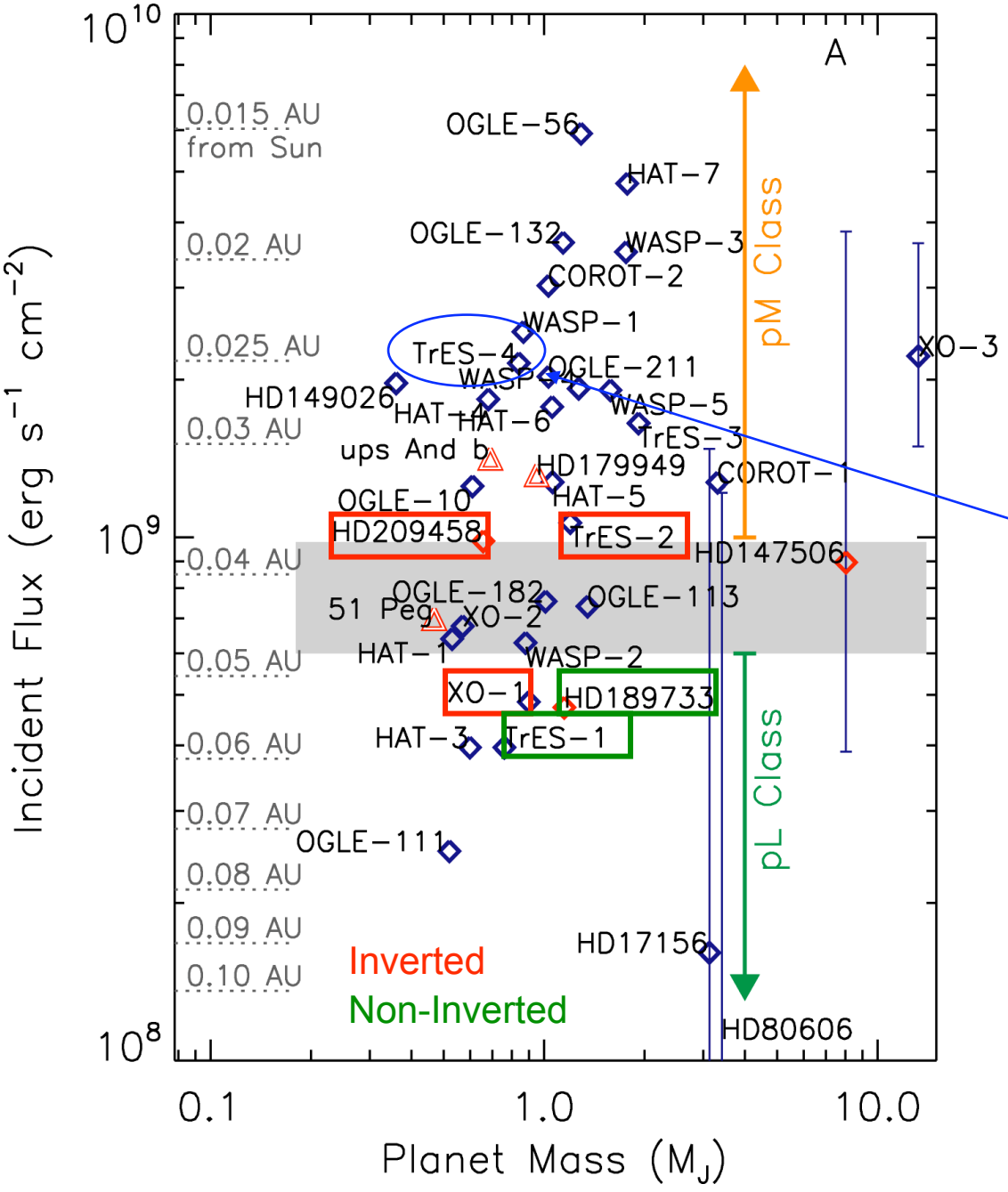


Requires a model with a temperature inversion and water features in *emission* instead of absorption.



Why so different?

HD 209458b receives 2x as much incident flux as HD 189733b…



Gas Phase TiO/VO

↓

Temperature Inversion?

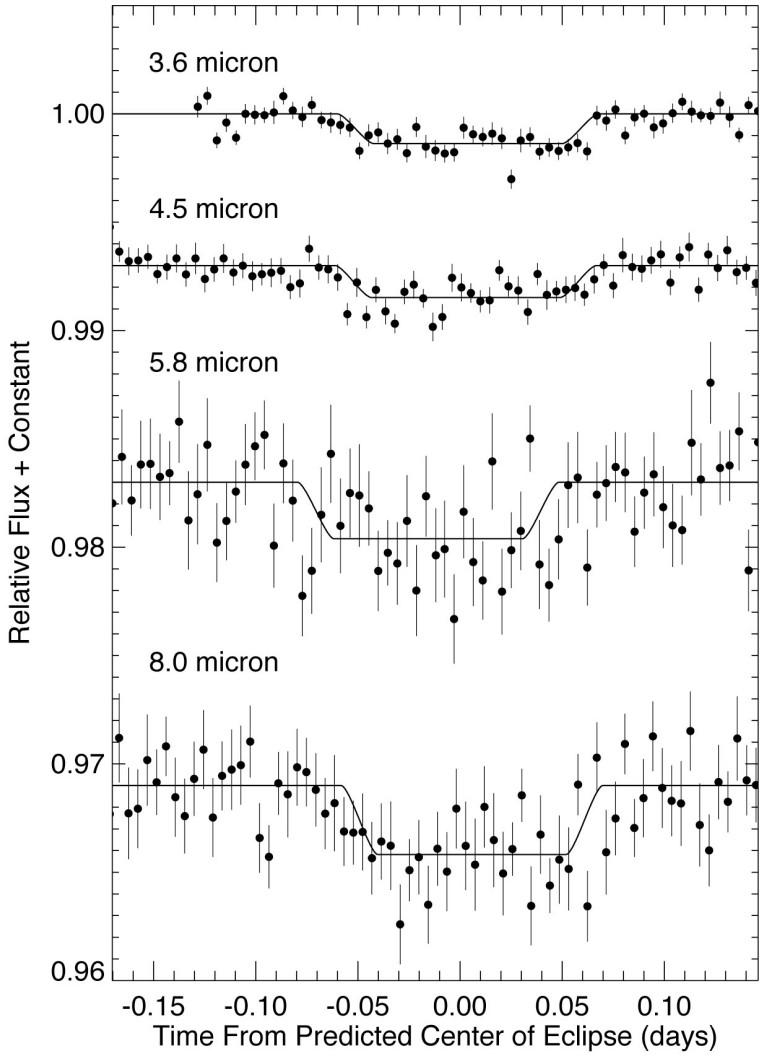
TrES-4 is a great test case!

T_{eq} = 1760 K

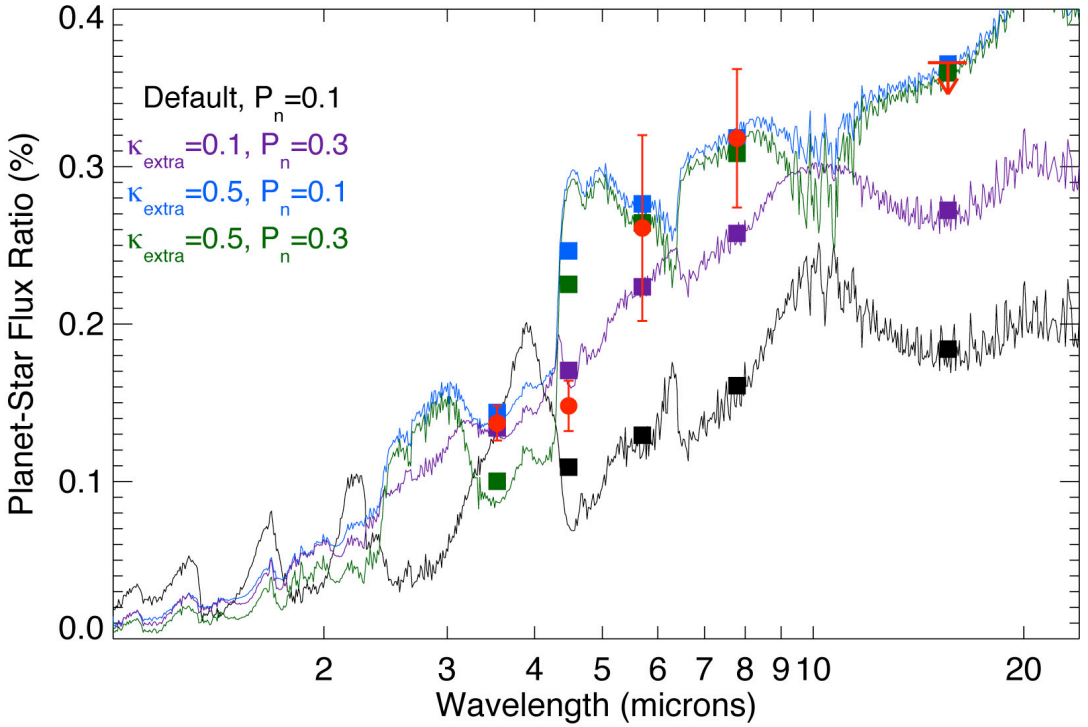
As described in Hubeny et al. (2003), Burrows et al. (2007, 2008), and Fortney et al. (2008)

Figure from Fortney et al. (2008)

Testing the Model: TrES-4



Incident Flux:
2×10^9 erg s^{-1} cm^{-2}
T_{eq} = 1760 K

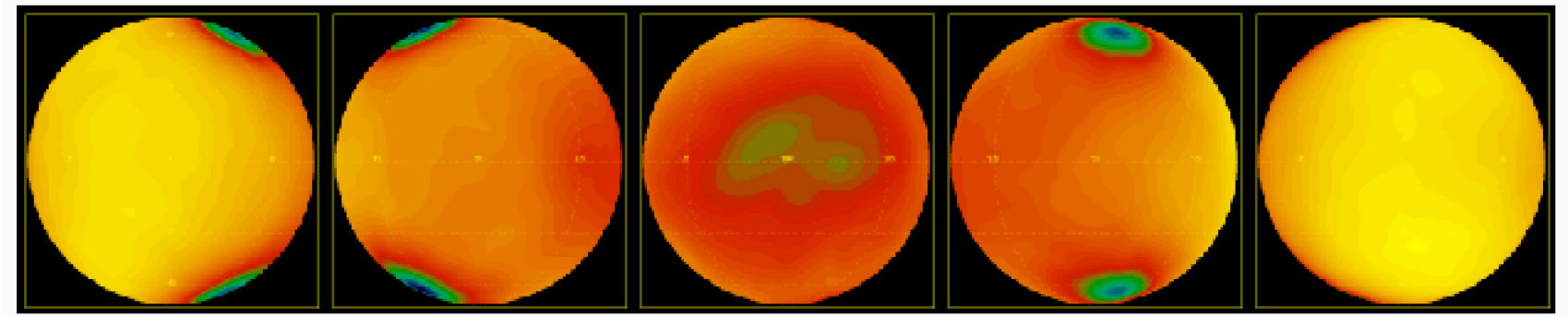


Figures from Knutson et al. (2008c)

Moving to 2D: Atmospheric Circulation Models

- Hot Jupiters receive ~20,000 times more radiation than Jupiter
- What happens to this energy?
  - Hot day side, cool night side
  - Winds -> homogenized temperatures
  - Rotating vortices?
- Answer depends on properties of atmosphere (radiative vs. advective timescales)

Model for HD 209458b by Cho et al. (2003, 2008). Figure from Rasucher et al. (2008). Temperatures range from 700 to 1400 K.



Mapping the Day-Night Circulation With Phase Curves

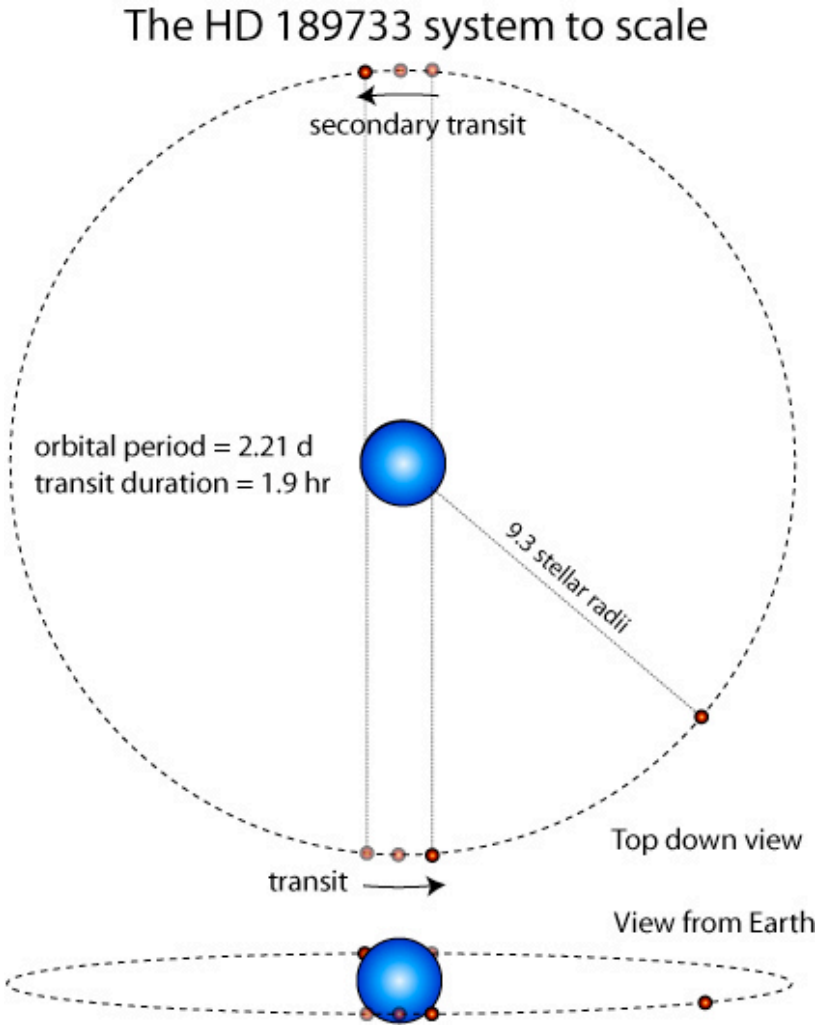
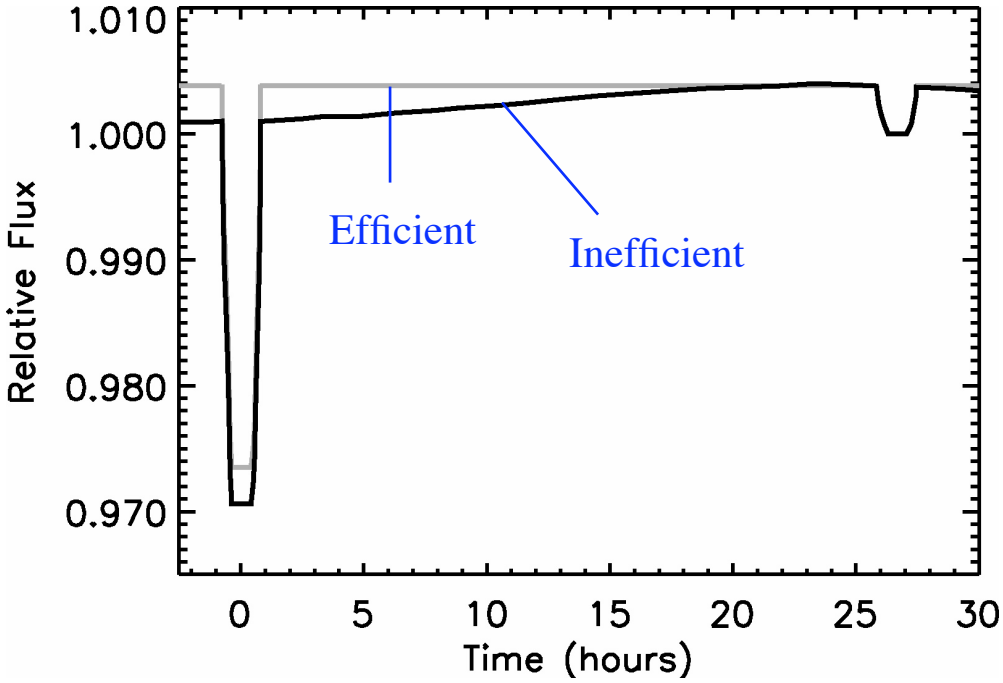
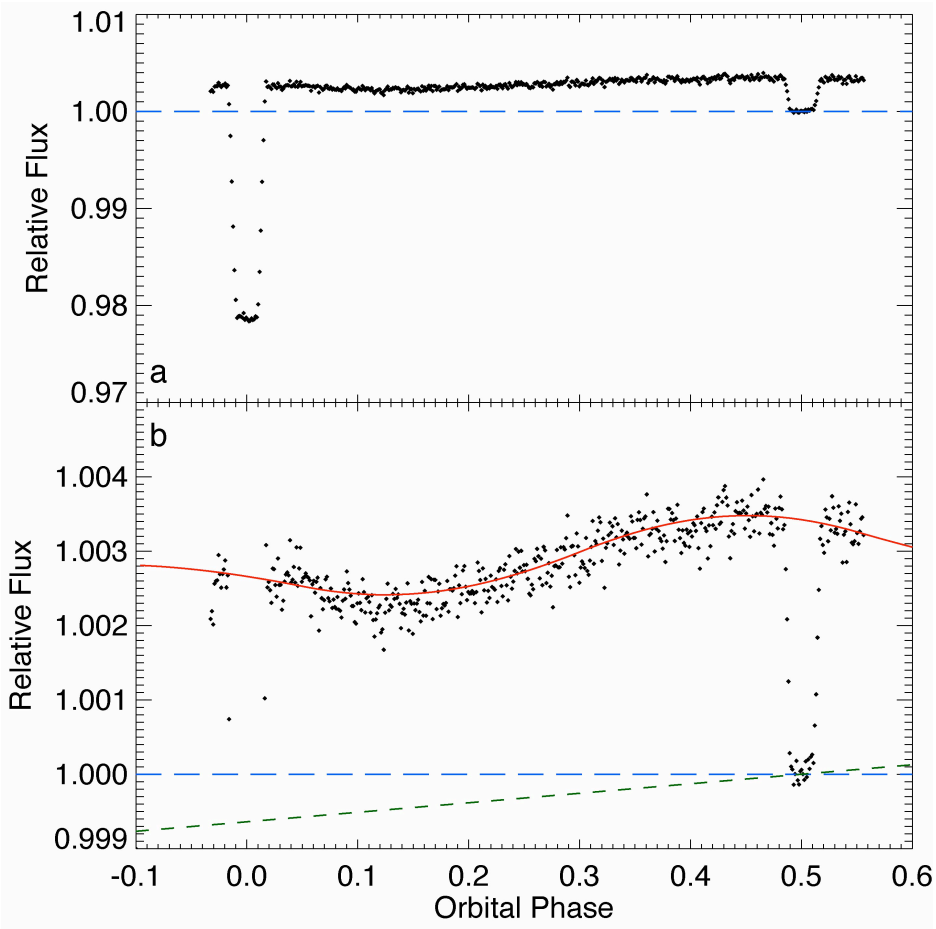


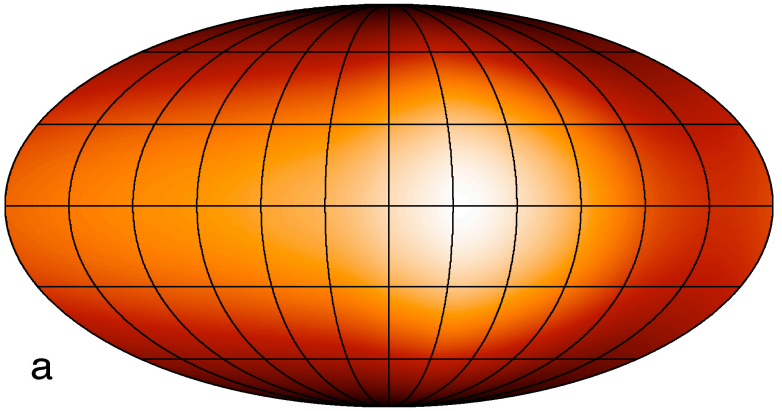
Image courtesy G. Laughlin

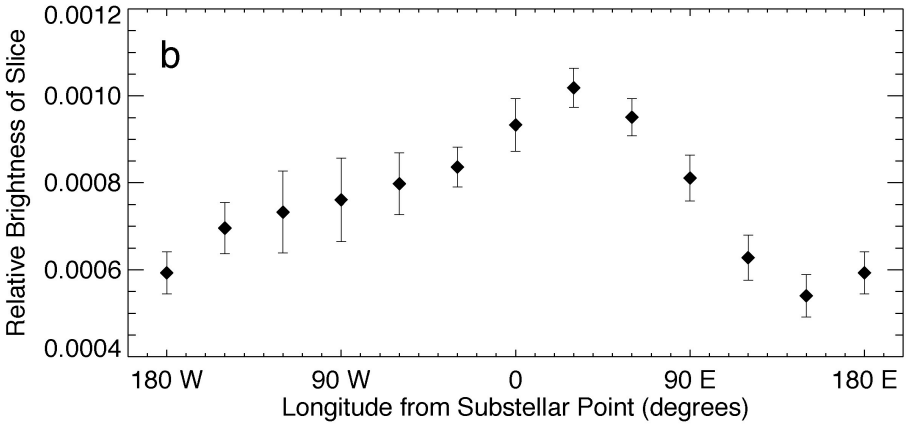
- Planets are tidally locked
- Size of variation depends on efficiency of day/night circulation



The Result: First Longitudinal Temperature Profile for an Extrasolar Planet

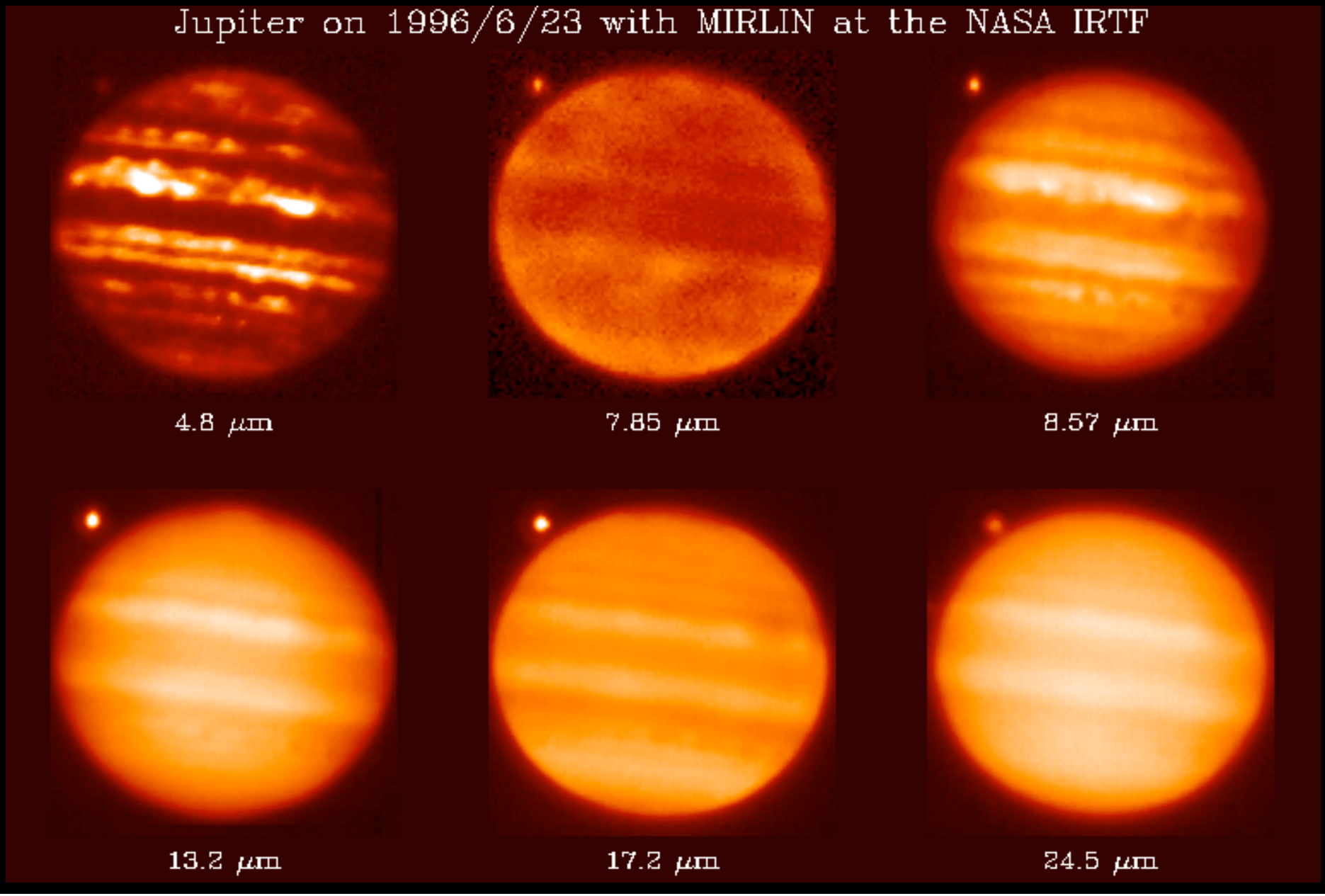






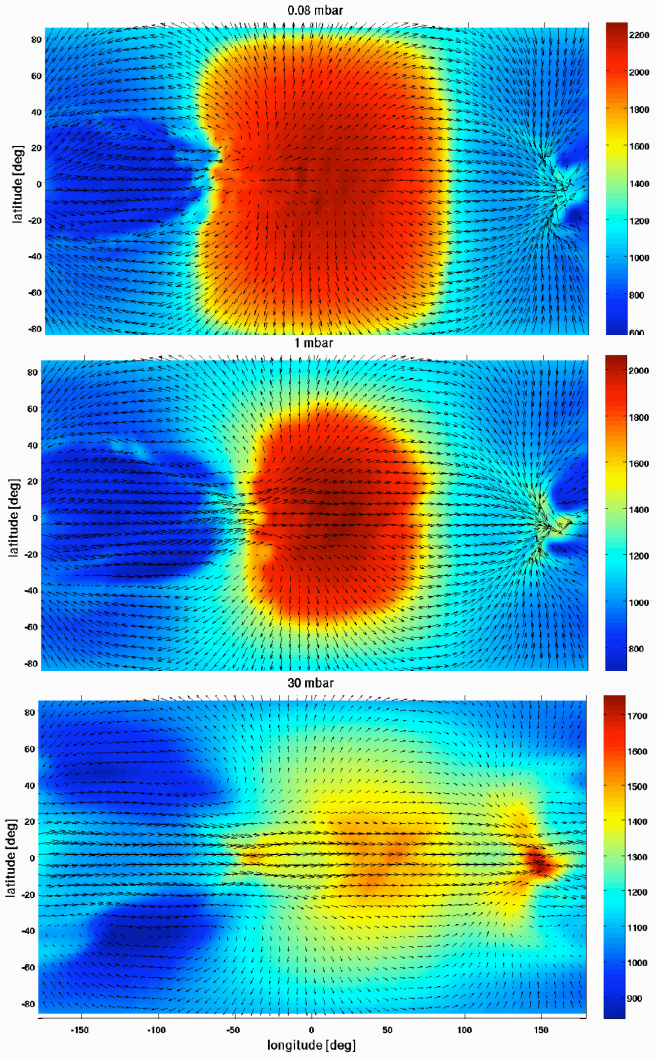
Figures from Knutson et al. 2007b, *Nature* 447, 183

The Need for Multi-Wavelength Observations

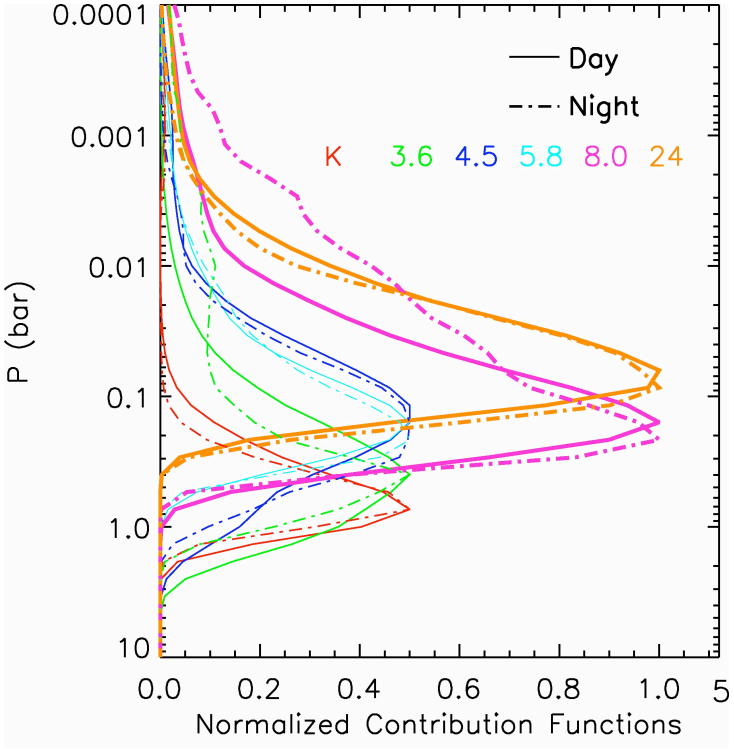


Atmospheric Circulation Models vs. Depth

Models indicate that day-night contrast should vary with depth…



… but how deep are we seeing?

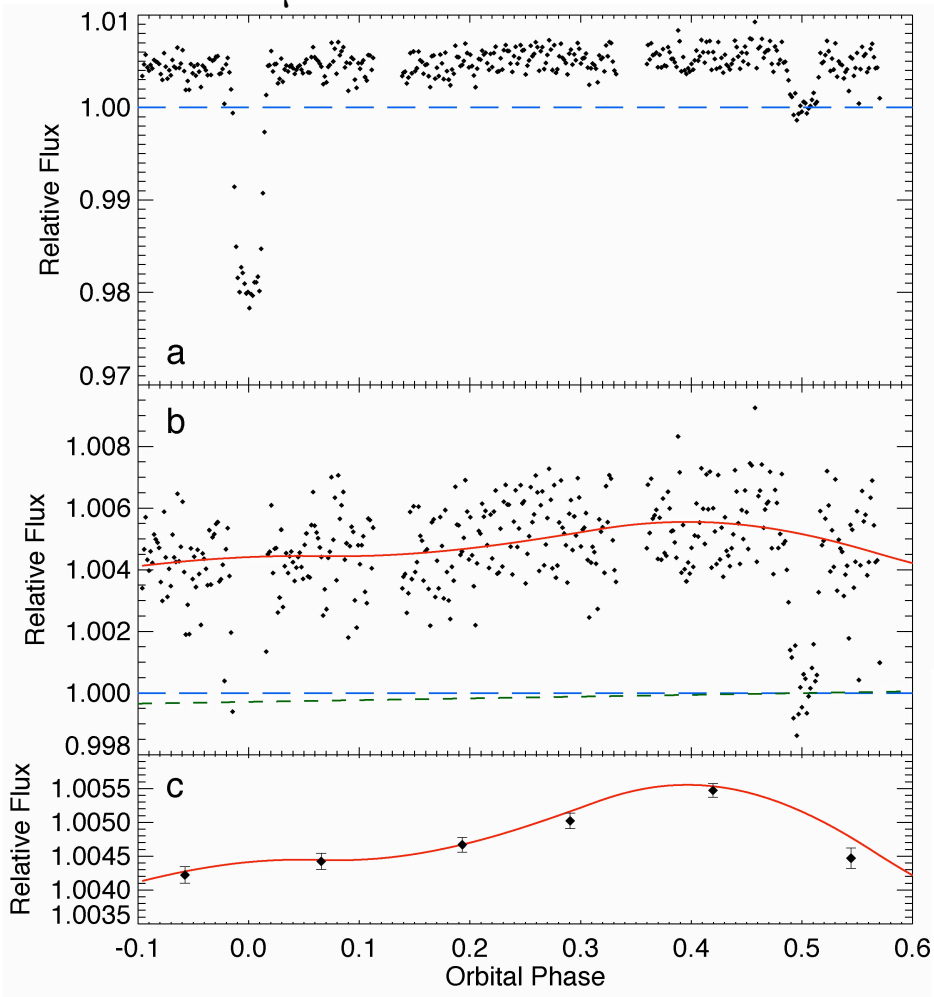


Normalized contribution functions for 1D model atmospheres of HD 189733b. The day side is plotted with solid curves while the night side uses dash-dot curves (Knutson et al. 2008b, Fortney et al. 2008).

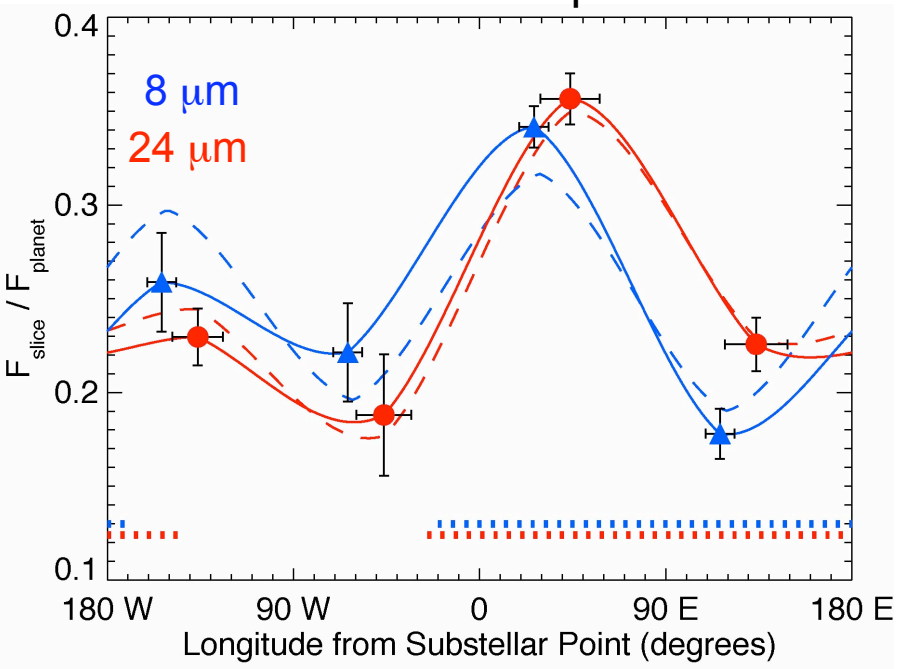
Showman et al. (2008)

Mapping HD 189733b at Two Wavelengths

24 μm MIPS Phase Curve



Two-Color Map

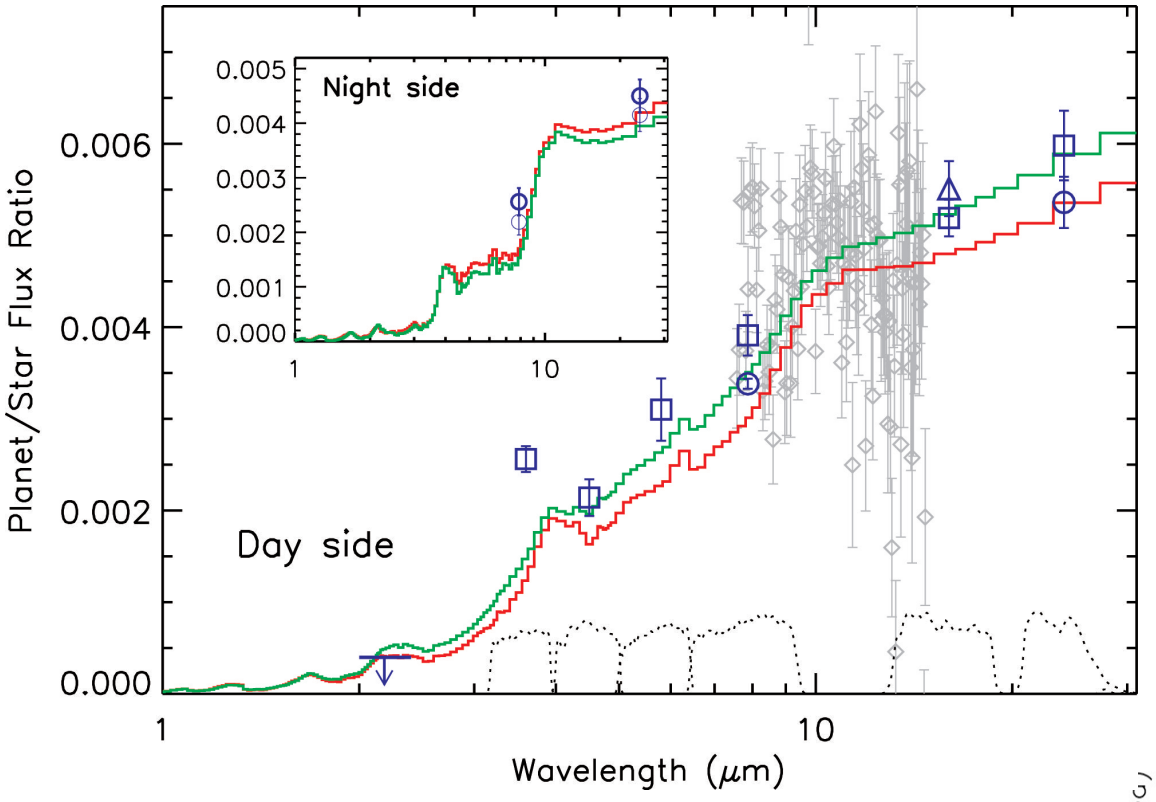


Figures from Knutson et al. (2008b). For more information on map fits, see Cowan et al. (2008).

Why so similar? Two possibilities:

1. Both wavelengths originate from the same pressure
2. Day-night contrast is similar over the relatively modest factor of ~2-3 in pressure sensed by these two wavelengths

A Global Energy Budget for HD 189733b

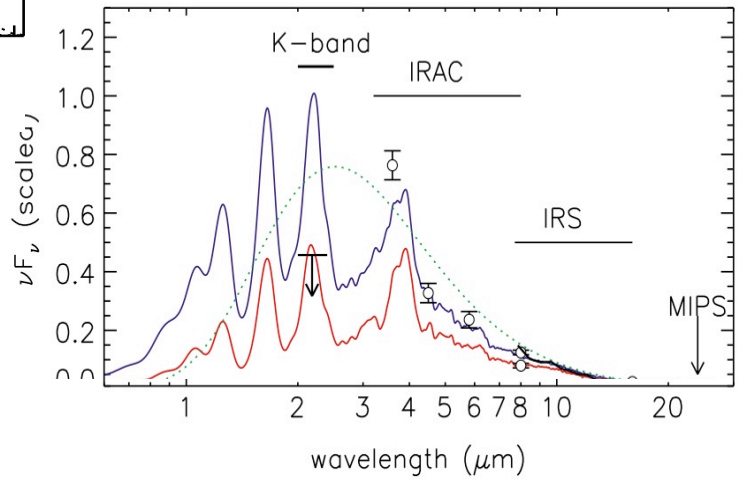


Knutson et al. (2008b), Charbonneau et al. (2008), Showman et al. (2008)

Both day- and night-side fluxes appear to be higher than predicted…

… increasing the atmospheric metallicity to 5x solar helps but isn't perfect.

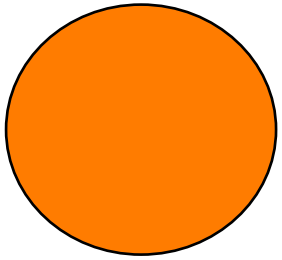
Important to constrain night-side flux near peak of planet's emission



Barman (2008)

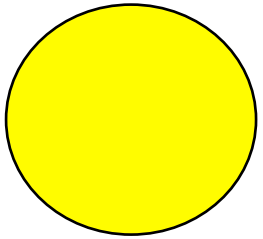
Next Steps: Expanding the Sample

How do temperature inversions affect the day-night circulation?



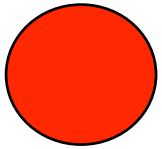
HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1360 K

Benchmark system



HD 189733b
Mass: 1.15 M_{Jup}
Radius: 1.15 R_{Jup}
T_{equil}=1130 K

Do core-dominated planets have qualitatively different circulation patterns?



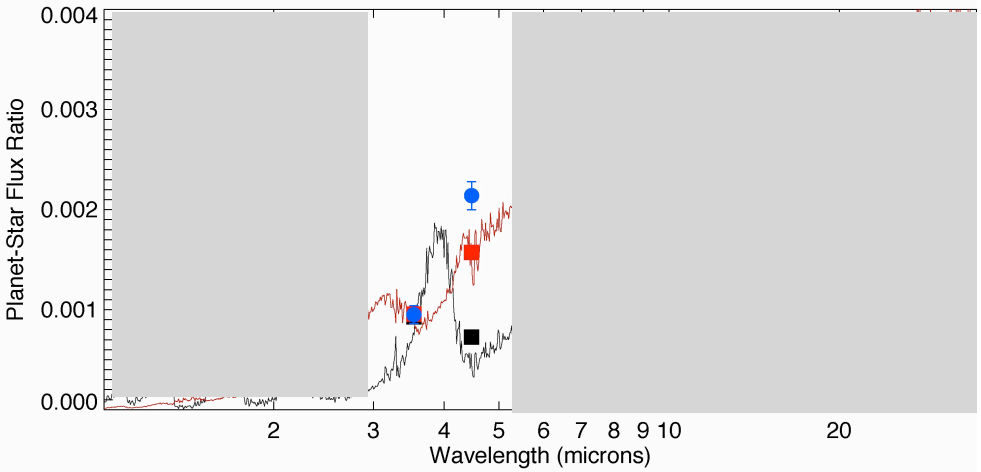
HD 149026b
Mass: 0.36 M_{Jup}
Radius: 0.76 R_{Jup}
T_{equil}=1650 K

What about a cool, eccentric, Neptune-mass planet?

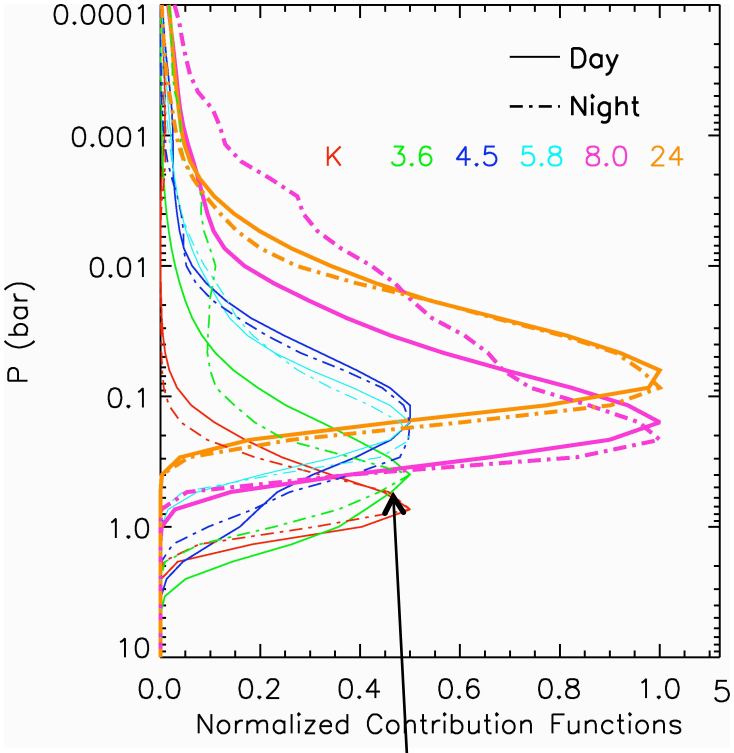
GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=670 K

Exoplanets & Warm Spitzer

Project 1: Survey for Temperature Inversions



Project 2: Phase Curves at 3.6 and 4.5 μm



3.6 μm looks deepest into atmosphere

What Are the Prospects for Finding Transiting Terrestrial Planets?

This is what we've observed so far

This is what we would like to observe

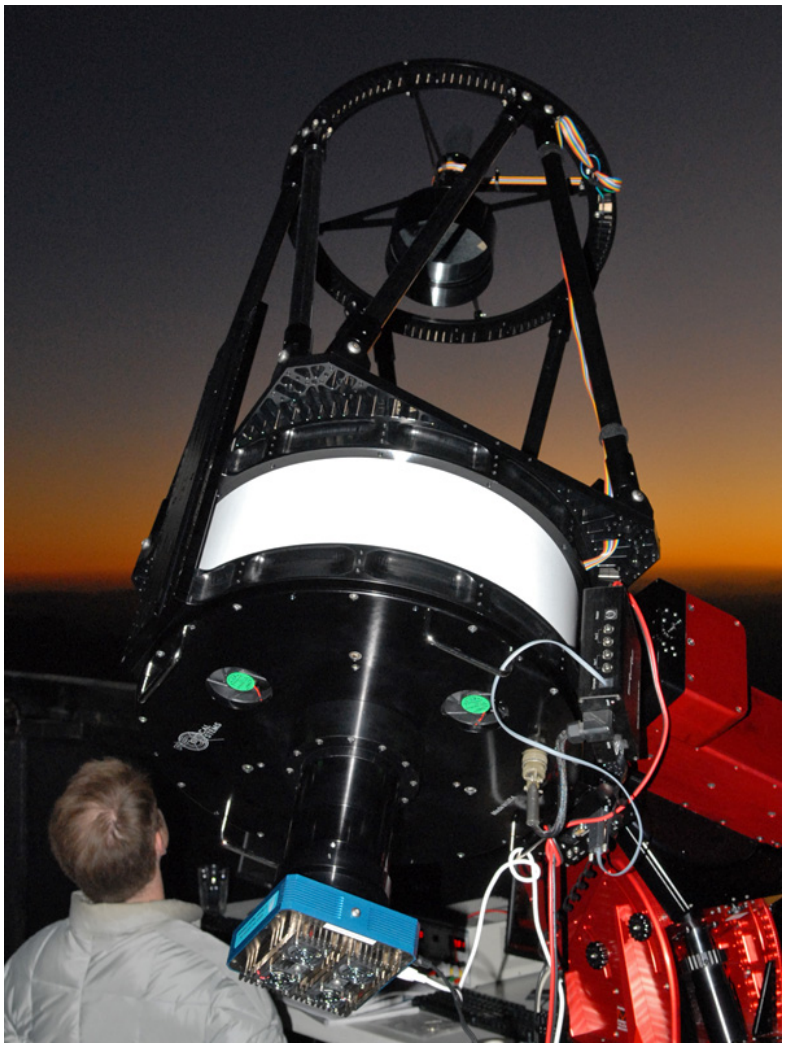
Jupiter's area is 120 times greater than the Earth's, and it has over 300 times the Earth's mass.

Space-Based Searches for Transiting Rocky Exoplanets

- CNES mission (with ESA)
- Launched 27 Dec 2006
- Will monitor 12,000 stars in each of 5 different fields, each for 150 days
- Sensitivity to planets > 2 R_{Earth}

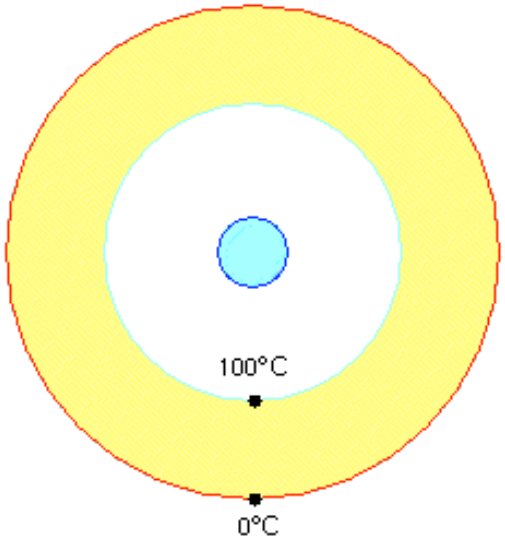
- NASA
- Schedule for launch on March 4 2009
- Will monitor 100,000 stars in a single field for 4 years
- Sub-Earth radius sensitivity
- Will determine rate-of-occurrence of Earth-like planets (or place upper limit of several percent)

Terrestrial Planets & the M Dwarf Opportunity

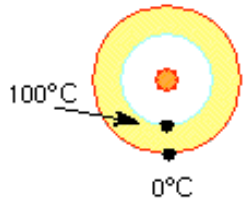


The MEarth Project

Habitable Zones Around Stars
Big and Small



Hot, luminous star



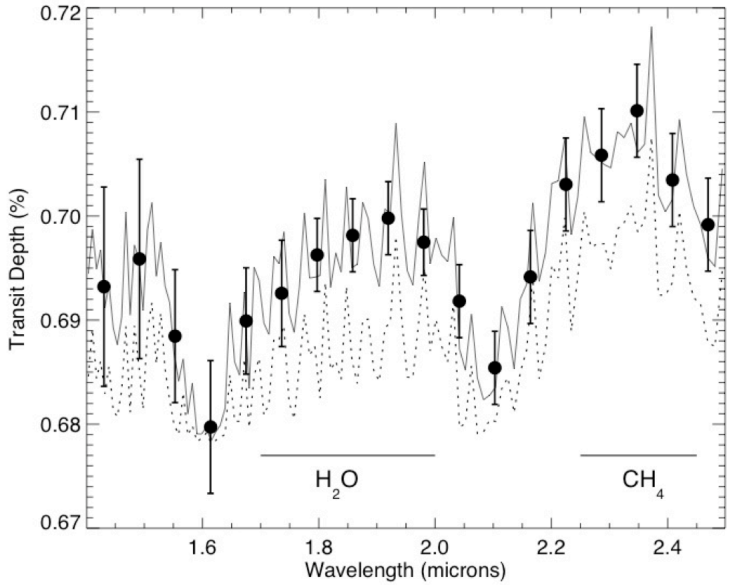
Cool, dim star

Image by Nick Strobel

Nutzman & Charbonneau (2008)
Irwin et al. (2008), astro-ph/0807.1316

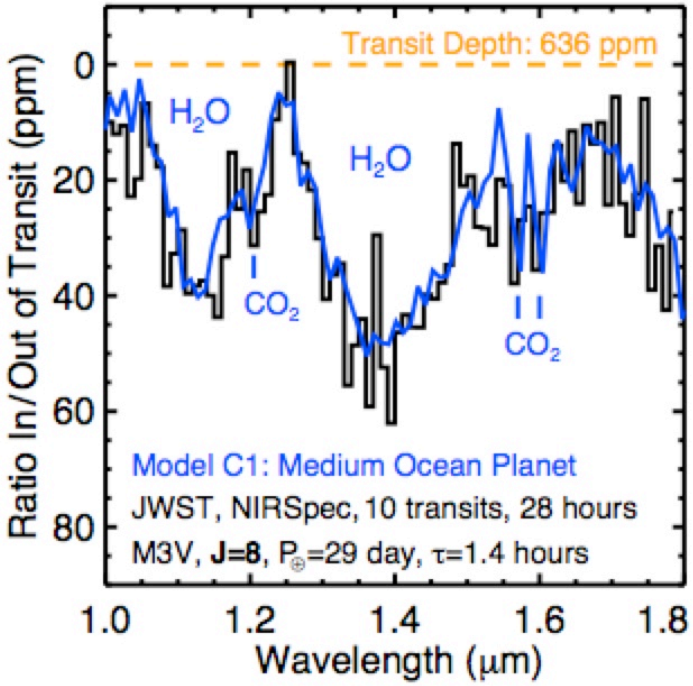
Prospects for Studies of Super-Earths (and smaller) with JWST

Neptune-mass planets are observable with Spitzer and HST….



Predictied transmission spectrum for 700 K, 22 Earth-mass planet GJ 436b from Miller-Ricci et al. (2008, in prep). Solid line is for solar -composition atmosphere, dotted line is 30x solar. Points show precision achievable with observations of 4 transits using NICMOS.

… but super-Earths will require JWST-level precision

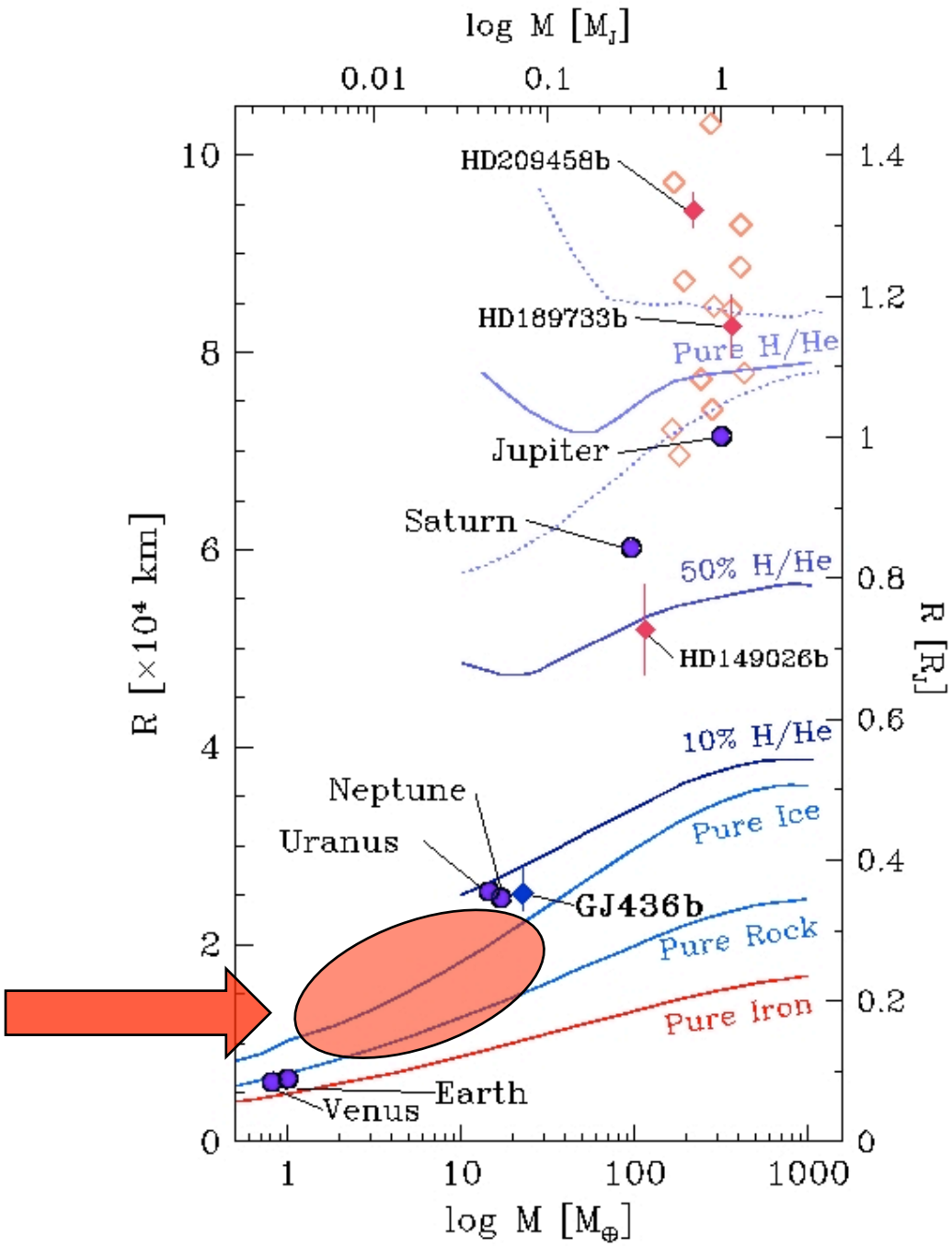


Predictied transmission spectrum for a 0.5 Mearth, 1 Rearth habitable ocean planet orbiting a M3V, J=8 star (Seager, Deming, & Valenti 2008). Models are from Ehnreich et al. (2006).

A Diversity of Worlds

Super-Earths & Mini-Neptunes

Mass range:
5-20 Earth masses



Conclusions

Transiting planets are an incredibly rich source of information…

.... which we have utilized to explore the complex, dynamic natures of hot Jupiters.

We are well-situated to take advantage of the coming explosion in smaller transiting planet systems!